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Transient Phenomena in Double Λ-Atom System: Coherent Population Transfer

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In recent years there is a great interest to transient phenomena in multilevel systems. Such transient phenomena both atom wave packet coherent scattering and coherent population transfer in the atom systems have many applications both in the area of sub-doppler laser cooling and for creation of the very efficient atom wave packet beam splitter [1]. We have to point out that the method of population transfer from one of lower levels of atom system to other one has been demonstrated in [2] at the first time. Its applications to atom interferometry [3] and laser cooling below temperature of photon recoil [4] have been proposed.

The basic problem for these applications is the efficiency of the coherent population transfer. It is known [2], that for three-level Λ-atom (Fig.1a) the efficiency of such transfer is determined by the relation between the amplitudes of time-delayed laser pulses $\mathbf{\Omega}_{1,2}$ with frequencies $\omega_{1,2}$ and time delay τ_d

$$\mathbf{\Omega}_0 \tau_d \gg 1, \tag{1}$$

where detunings of laser waves are equal to zero and we assume that both laser pulses have the Gaussian shapes with the same amplitudes equal to $\mathbf{\Omega}_0$ (Fig.1a). When the relation (1) is valid, the efficiency of population transfer closes in 100 per cents and in a result all population can be transfered from the level $|1\rangle$ to the level $|2\rangle$ of Λ-atom. It is important, that such population transfer occurs without populating of the excited state $|3\rangle$ during of laser pulse action. The such coherent transfer (when the condition (1) is valid) is called the stimulated Raman adiabatic passage (**STIRAP**) and the ideal **STIRAP** process is a coherent one. Note also that the efficiency of such process as **STIRAP** depends only weakly on the shape of laser pulses (that is why it does not matter what kind of pulse shapes there are in (Fig.1a)). The different types of the laser pulse shapes as well as non-adiabatic regimes for these pulses studied in [5].

On the other hand, there are a few works [6], where **STIRAP** in the multilevel atom systems has considered. However, up to now the coherent population transfer is not considered for atom systems with closed countour of interaction [7,8]. The simplest closed atom system, with the interaction contour closed only by optical fields is double Λ–system (Fig.1b). The such atom system was investigated in the context both laser cooling [7] and four wave mixing [8]. [1] In the this cases the efficiency (e.g. laser cooling) has depended on the phases of exciting waves [7,8] and we can look forward that the same phase dependence occurs for the coherent population transfer in multilevel atom systems with closed interaction contour.

In this paper we investigate the coherent population transfer in the double Λ–system (Fig.1b) with the closed contour of interaction between optical waves and atomic transitions. We will show below that the efficiency of the coherent population transfer in the double Λ–system dependes on the phase of atom contour. Thus, for the zero–phase value the efficiency of the coherent population transfer is close to **STIRAP** for three-level atom system. At the same time, the coherent population transfer efficiency is equal to zero for the phase value equal to π. As a result, the atomic population is not transfered from one of the lower levels of double Λ–system to other one even if the usual adiabatic condition as (1) is valid. We will show also that for the case of the double Λ–system the adiabatic condition like (1) which determines the coherent population transfer efficiency, has to be supplemented by the condition on the phase value of the closed interaction contour.

Let us now consider the double Λ–atom system, excited by an optical field of four running waves with different frequencies ω_m (m=1-4)

$$\vec{\mathbf{E}} = \mathbf{E}_0[\vec{\mathbf{e}}_1 \exp(-(t-\mathbf{T}_1)^2/\delta\tau^2)[\exp(i\omega_1 t + i\chi_1) + \exp(i\omega_3 t + i\chi_3)]$$

$$+\vec{\mathbf{e}}_2 \exp(-(t-\mathbf{T}_2)^2/\delta\tau^2)[\exp(i\omega_2 t + i\chi_2) + \exp(i\omega_4 t + i\chi_4)]] + c.c., \mathbf{T}_1 - \mathbf{T}_2 = \tau_d, \quad (2)$$

where $\vec{\mathbf{e}}_{1,2}$ are the polarization vectors, χ_m are initial phases and $\mathbf{E}_0$ is the amplitude of laser waves (m=1–4). We shall assume also that the transitions l-n (l=1,2; n=3,4) forming the closed interaction contour (which charactere) are electric dipole transitions, while the trasitions $|1\rangle$–$|2\rangle$ and $|3\rangle$–$|4\rangle$ are forbidden in the dipole aproximation (Fig.1) and that the spontaneous relaxation in such system is absent as well.

Now we will consider double Λ–atom interacts with two time–delayed laser pulses, which have Gaussian shape, and each of this pulses consists of two-frequent optical waves with frequencies $\omega_{1,3}$ and $\omega_{2,4}$ (Fig.1a).

We have specially to stress, that both double Λ atom systems, which is shown in Fig.1b, is equivalent and the results which will be obtained below are valid for both atom level systems.

To investigate the coherent population transfer problem in double Λ– system by interaction with the field of light waves (2) in the condition of multifrequent resonance $\omega_1 - \omega_2 = \omega_3 - \omega_4$, we write immediately the system for time-depended amplitudes of probabilities $a_m(p)$ for the states of atom system as [8]

$$i\frac{da_1}{dt} = \Omega_1(t)[a_3 + a_4 \exp(-i\Phi)],$$

[1] Recently experiments on investigation of four wave mixing in sodium vapor cell have been performed by group of Dr. P.Hemmer from Rome Laboratory. It has been shown in these experiments that generation of a phase-conjugate wave takes place at large detuning of a pumping wave from the resonant transition in a double Λ system of atomic levels only (so called case of Raman interaction). Moreover, the experiments demonstrated high efficiency of such Raman interaction for generation of the conjugate wave with low intensities of the exciting waves [9], that indicates realization of new type of Raman laser [10].

$$i\frac{da_2}{dt} = \Omega_2(t)[a_3 + a_4], \tag{3}$$

$$i\frac{da_3}{dt} = \Omega_1(t)a_1 + \Omega_2(t)a_2,$$

$$i\frac{da_4}{dt} = \Omega_1(t)a_1\exp(i\Phi) + \Omega_2(t)a_2,$$

where

$$\Omega_{1,2} = \Omega_0\exp(-(t - \mathrm{T}_{1,2})^2/\delta\tau^2)$$

are the time-depended Rabi frequencies with amplitudes which we will assume the same for all transitions in double Λ system, $\mathbf{\Phi}$ is the common phase of atom contour. In the simplest case $\mathbf{\Phi}$ is determined by initial phases of laser waves by $\Phi = \chi_1 - \chi_2 + \chi_4 - \chi_3$. We assume also that for all laser waves the detunings are equal to zero.

Having solved the equations (3) numerically, we have obtained the time dependence of the populations of double Λ–states. Thus, Fig.2a shows one the coherent population transfer for the case when the value of the atom contour phase $bf\Phi$ is equal to zero. Initially, only the level $|1\rangle$ of double Λ–system was populated and adiabatic condition like (1) is valid.

As can be seen from Fig.2a, the efficiency of coherent population transfer is very high and all population from low state $|1\rangle$ to other low state $|2\rangle$ of the double Λ–system is transfered during time period of the laser pulse action. The such behaviour of the population is very close to the **STIRAP** case in the three-level atom system [ ]. Note also, that in this case the populations of the upper states $|3\rangle$ and $|4\rangle$ are equal to zero during of the action of laser pulses and such coherent population transfer can be assumed as actually **STIRAP** process. The efficiency of the coherent population transfer is high again if the phase value equal to $\pi/2$ but the upper states of double Λ–system already are populated. (Fig.2b). At last, Fig. 2c demonstrates the time–dependence of the populations of the double Λ states for the phase value equal to π. In this case, the population is not transfered from the level $|1\rangle$ to the level $|2\rangle$. In other words the efficiency of coherent population transfer is always equal to zero for $\mathbf{\Phi} = \pi$.

The dependence of the coherent population transfer efficiency on the atom contour total phase $\mathbf{\Phi}$ is shown in Fig.3 (condition similar to (1) is valid). The variation of the phase Φ demonstrates the change of the coherent transfer character. So, for the phase values of atom contour differ from $\pi(2n+1)$ we observe high efficiency of coherent population transfer because, as one can be sce from Fig.3, the population of level $|2\rangle$ is close to one after action of laser pulses. Note, that initially the state $|2\rangle$ of double Λ–system is not populated while the all population of atom system are grouped on the state $|1\rangle$. At the same time, for $\mathbf{\Phi}_{dest} = \pi(2n+1), (n = 0, 1, 2, ..)$ the level $|2\rangle$ of double Λ-system is not populated for any Rabi frequencies of laser waves. It means that the coherent transfer efficiency is equal to zero. Such behaviour of the coherent population transfer is conditioned by the destruction of coherency between the lower states $|1\rangle$ and $|2\rangle$ of double Λ atom (Fig. 1b) for the atom contour phase $\mathbf{\Phi} = \mathbf{\Phi}_{dest}$ anologous to the manifestation of the coherent population trapping in the same atom system [7]. If now the Rabi frequency is increasing, the phase area where the efficiency of coherent transfer is high increases as well. However, for the phase value Φ_{dest} the efficiency of the coherent transfer is always equal to zero despite to the fact that the adiabatic condition (1) is valid for considered values of the Rabi frequency. This suggests that in the case of double Λ–system the abiabatic condition (1) has to be supplemented by the dependence on the atom contour phase Φ. As a result the new condition for the high efficiency of population transfer in the case of double Λ–system can be written as

$$\Omega_0 \tau_d \cos^2[\Phi/2] \gg 1, \tag{4}$$

As can be seen from (4), the condition of high efficiency of coherent population transfer as (1) occurs when the phase value differs from Φ_{dest}. For the phase value Φ_{dest} such condition (as (1)) is never carried out (Fig.3).

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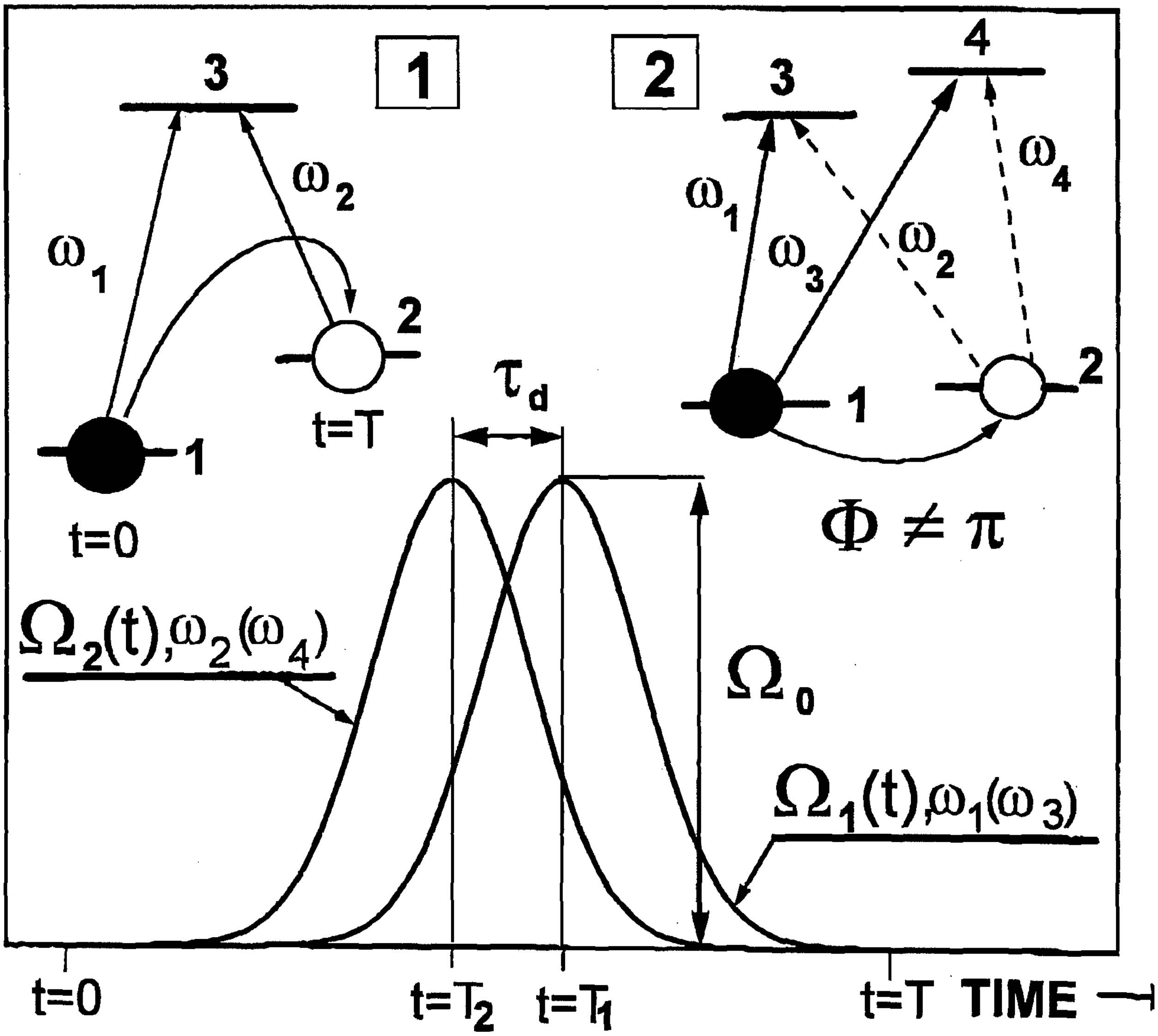

Fig.1a Coherent population transfer in three-level atom system (1) and in double Λ-system (2) for the phase value is not equal to π. The first light pulse consists of laser waves with frequencies ω_1, ω_3 for double Λ-system (or have laser frequency ω_1 for three-level atom system), while the second light pulse has the frequencies ω_2, ω_4 (or only ω_2 for Λ system). Ω_0 is Rabi frequency amplitude which is the same for both light pulses, τ_d-delayed time between laser pulses.

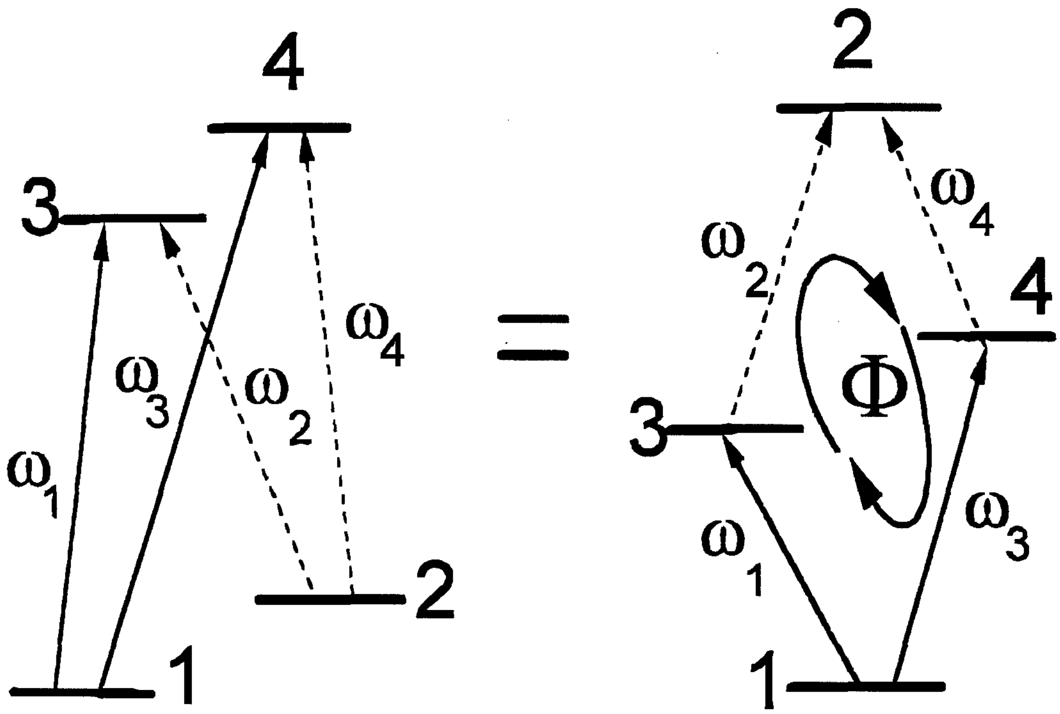

Fig.1b Two type of double Λ-atom systems.

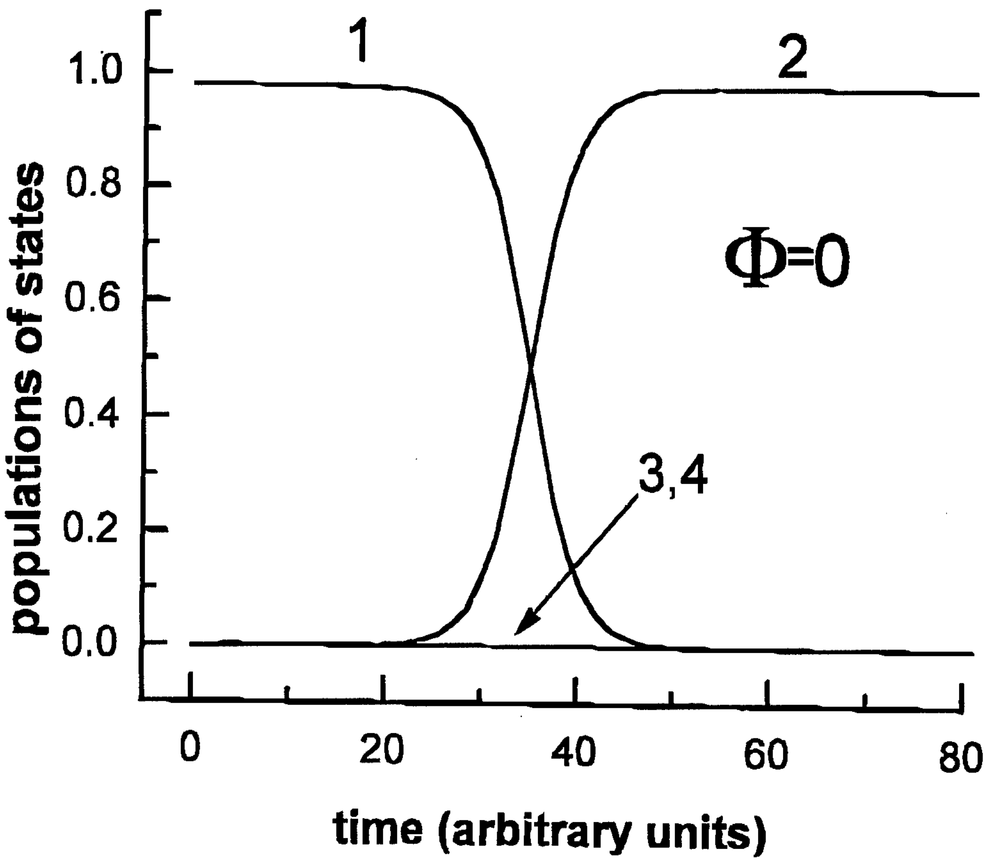

Fig.2a Time-depended populations of double Λ-atom states for the phase value of atom contour equal to zero ($\mathbf{\Phi} = 0$). Laser pulses have the Gaussian shapes with $\delta_T = 10$ which are centred on $\mathbf{T}_1 = 40, \mathbf{T}_2 = 30$ while $\tau_d = 10$ (all times in arbitrary units). The amplitude $\mathbf{\Omega}_0$ of time-depented Rabi frequency is equal to $\mathbf{\Omega}_0 = 5MHz$. As we can see in this case the efficient coherent population transfer is observed.

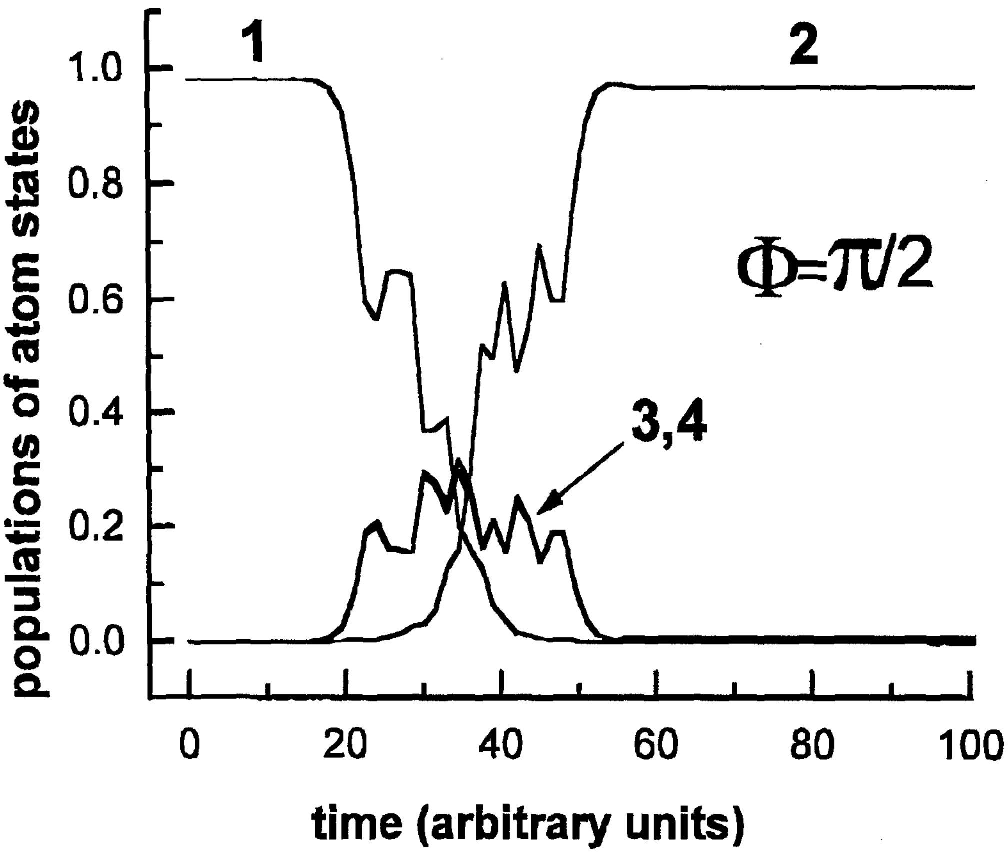

Fig.2b Time-depended populations of double Λ-atom states for the phase value of atom contour equal to $\pi/2$ ($\Phi = \pi/2$). Other parameters are the same as last figura.

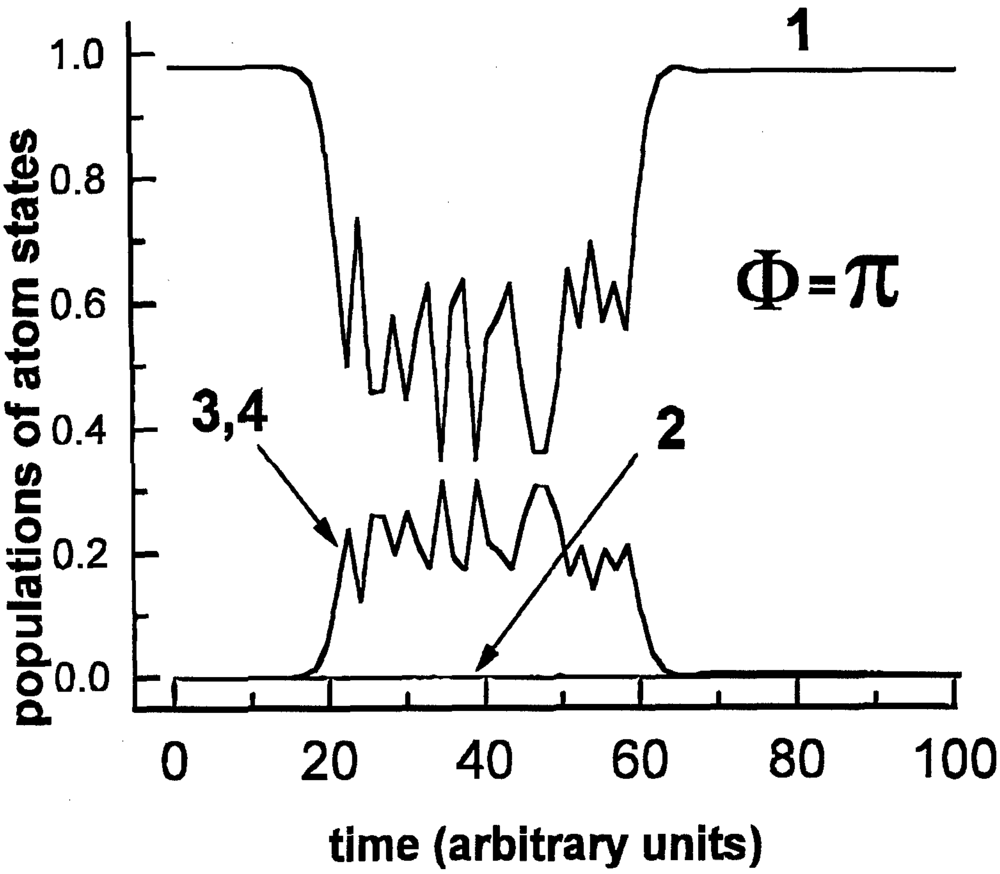

Fig.2c Time-depended populations of double Λ-atom states for the phase value of atom contour equal to π ($\Phi = \pi$). For this value of phase contour the population transfer between lower states of double Λ-atom system does not observe at all.